

Assessing the Altimetric Measurement from CYGNSS Data

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ABSTRACT

The Cyclone Global Navigation Satellite System (CYGNSS) mission was designed to study hurricane intensification by measuring wind speeds in tropical cyclones. However, the delay-Doppler maps (DDM) that are produced can be used to estimate the sea surface height (SSH) at the specular reflection point on the ocean surface. Proof-of-concept studies that DDMs are suitable to solve for SSH have been recently reported (*Clarizia et al., 2016; Mashburn et al., 2018*), based on data acquired by the demonstration satellite experiment Tech Demo Sat - 1 (TDS-1) carrying a GNSS-R receiver similar to the ones onboard CYGNSS. Although the precision of each 1-sec averaged SSH is considerably lower than that of the existing satellite altimeters, by virtue of the dense coverage and frequent revisit time exhibited by the constellation of 8 microsats, the error may be smoothed down considerably by optimal interpolation (*Li et al., 2016*). Hence the CYGNSS dataset presents a potential opportunity to sample the tropical oceans, and investigate the

sensitivity of the SSH measurements to mesoscale eddies.

Our objective is to analyze the CYGNSS data and test a suite of retrieval algorithms, including that of *Mashburn et al., 2018* to obtain SSH, to understand the error sources and possible corrections when available. Because of the limited antenna gain of the CYGNSS instrument, the power SNR for general wind conditions is expected to be too low to accurately track the reflection point contribution, resulting in altimetry errors of the order of several meters. Other significant error sources are the CYGNSS satellites orbit knowledge, the ionosphere, the troposphere, the mean sea surface and the tides; some of these errors can be reduced by using models. The corrected SSH data will be assimilated into the ROMS high-resolution ocean model to investigate their ability to reproduce mesoscale eddies in the tropical oceans.

We have focused first on the region of Indonesia, site of the “Indonesian through-flow” (ITF), a system of surface currents flowing from the Pacific Ocean to the Indian Ocean through the Indonesian Seas. This is important because it is the only low latitude transport between oceans, particularly since one of the oceans is the warm Western Pacific. The ITF is associated with large seasonal SSH gradients, where the anomalies change sign seasonally and the changes can be of order ~ 0.5 meters. In this region past investigations with Ku-band altimeter data have revealed the presence of blooms in the backscattering cross section, corresponding to dramatic increases of the peak returned power (Mitchum *et al.*, 2004; Tournadre *et al.*, 2006; Ermakov *et al.*, 2011).

Figure 1 illustrates the CYGNSS reflections collected over the Indonesian sea in two days in August 2017. These 1Hz measurements are averaged into 0.5deg bins and colored to show correlation SNR and waveform width. Note the areas where peak powers are consistently very high, and the correspondent widths of cross-correlation waveforms (cross section of DDM at zero Doppler) are narrow, indicating that a coherent component is present. In such case the shape of the reflected signal is very similar to that of the direct signal, and the measurement of the delay between the direct and reflected peaks can be immediately related to the instantaneous SSH, from knowledge of the geometry of the reflection. This situation offers a test case for higher than average reflected power but requires implementing a tracking approach not predicated on only rough surface reflections. This region presents us with the opportunity to test the accuracy of the ocean altimetry measurement from CYGNSS

for a case with strong seasonal variation of the mean signal.

To investigate the characteristics of the Indonesian reflections, simulations were generated using the new ocean scattering model of Voronovich and Zavorotny, 2018 that accounts for the presence of coherent scattering in addition to the more common incoherent contribution. This model predicts an increase of ~ 9 -20 dB in the peak power SNR of 1-second waveforms depending on the reflection geometry resulting from coherent reflections manifesting at very low (< 3 m/sec) wind speed.

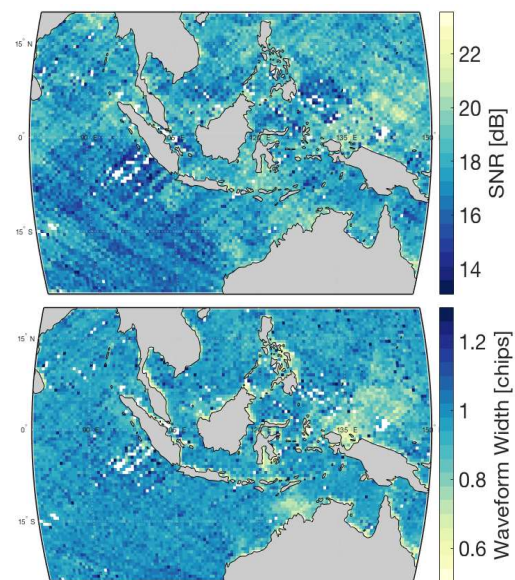


Figure 1. (top) Peak SNR and (bottom) Width of waveform at 70% of peak value, averaged over bins of (0.5×0.5) degree.

Observations from CyGNSS are qualitatively consistent with the modeled waveforms. An observed average increase of 8dB in SNR is associated with coherent reflections in the CYGNSS data of Fig. 1. Figure 2 shows two examples of normalized coherent and diffuse scattering modeled waveforms compared directly with low and high wind speed measurements. Coherent reflections are associated to relatively smooth surfaces

present in this region as a result of algal bloom and absence of swell.

We have implemented three algorithms for

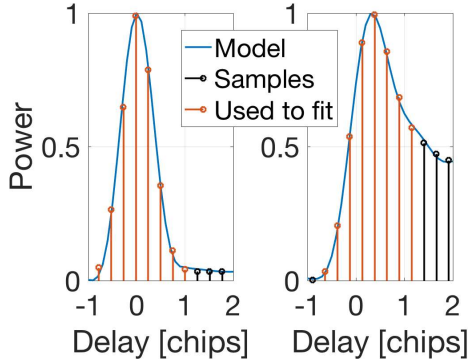


Figure 2. Modeled and measured power waveforms when coherent scattering is present (left) and for diffuse scattering (right). Incidence angle = 21deg.

altimetric delay retracking; (a) a waveform tracking method, (b) a full DDM tracking method, and (c) a waveform derivative method introduced in *Hajj and Zuffada, 2003*. Algorithm (a) builds upon previous point tracking techniques, *Mashburn et al., 2018*, to utilize more samples in the DDM measurement and improve performance in the presence of variable surface roughness conditions. The *waveform tracking* (dubbed “VZ18”) seeks the least-squares best fit between the data and a model of the waveform obtained using *Voronovich and Zavorotny, 2018* updated scattering model and solves for the location of the specular reflection point (example fits are seen in Fig. 2). The *Voronovich and Zavorotny, 2018* model is constrained to the observed reflection geometry of each case and evaluated over a range of wind speeds from 2-8m/s. Each model and measured power waveform is normalized to magnitude 1 and they are fit over delay.

The *full DDM tracking* method (“E2E”) estimates the altimetric delay by minimizing

the error between the measured DDM and a simulated DDM that has been generated using the CYGNSS End-to-End Simulator (*O'Brien 2014*). Since this method utilizes nearly all pixels in the DDM, it is expected to reduce noise at the expense of spatial resolution. Several parameters of the simulated DDM (altimetric delay, Doppler, ocean MSS, etc) are varied with very fine resolution until the total mean-square error with the data has been minimized.

The *waveform derivative* (“DER”) does not rely on any model and is directly derived from fitting a cubic spline to the data and taking the derivative of the fit with respect to the delay. The point corresponding to the maximum of the derivative is taken to be the specular point.

A preliminary performance comparison between these three tracking methods is presented in Fig. 3. For the VZ18 and E2E techniques, the input CYGNSS DDMs have been averaged for 10 seconds. For the DER technique, the 1Hz derived height is average for 10 seconds for comparison. The VZ18 and E2E techniques resolve the same periodic trend over the ~100 second track, have comparable noise in the retrieval, and show an overall height bias of ~3.5m.

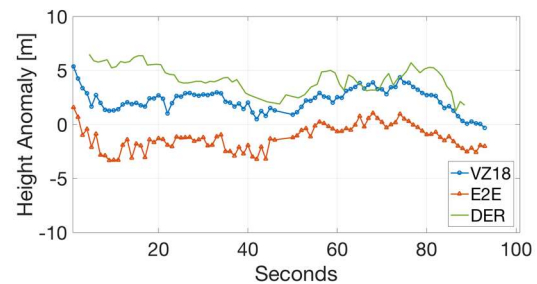


Figure 3: An along track comparison of the final height errors resulting from the waveform (VZ18), full DDM tracking (E2E), and derivative

(DER) methods. Retrievals are based on 1Hz data averaged down to 0.1Hz.

As stated earlier, the signal path delay is affected by known sources of error; one of the objectives of this study is to establish the magnitude of such errors as well as their main statistical properties. A preliminary error budget, for the track shown in Figure 3, based on the analysis methods from *Mashburn et al., 2018*, is reported in Table 1. The contribution of each error source is mapped to a delay error and broadly categorized as an RMS noise or a systematic term. The latter reflects a bias or slowly varying term for a short pass, but potentially varying over larger spatial and time scales. The CYGNSS orbit contribution is estimated based on orbit overlap statistics. The waveform retracking error is the standard deviation of residuals for these passes after removing a 5th order polynomial. GPS orbits are based on IGS data products (Dow et al. 2009).

Table 1

Error Source	Uncertainty in Delay
CYG Orbit	1.9 m (systematic)
GPS Orbit	0.05 m (systematic)
Tides	0.19 m (systematic)
Ionosphere	4 m (day, RMS) 2.2 m (night, RMS)
Troposphere	0.05 m (RMS)
Antenna Baseline	0.002 m (systematic)
Tracking Error	0.9 m (VZ18, RMS) 1.2 m (E2E, RMS)
RSS	~4.5/~3 m (day) (night)

In the coming months, as we expand the analysis over a larger set of data, we plan to investigate improvements in ionospheric corrections using GIM, and improvements in CYGNSS orbit estimates using downloaded pseudorange and carrier phase data instead

of onboard point solutions.

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